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Seismic resilience: concept, metrics and integration with other hazards

Georgios Tsionis

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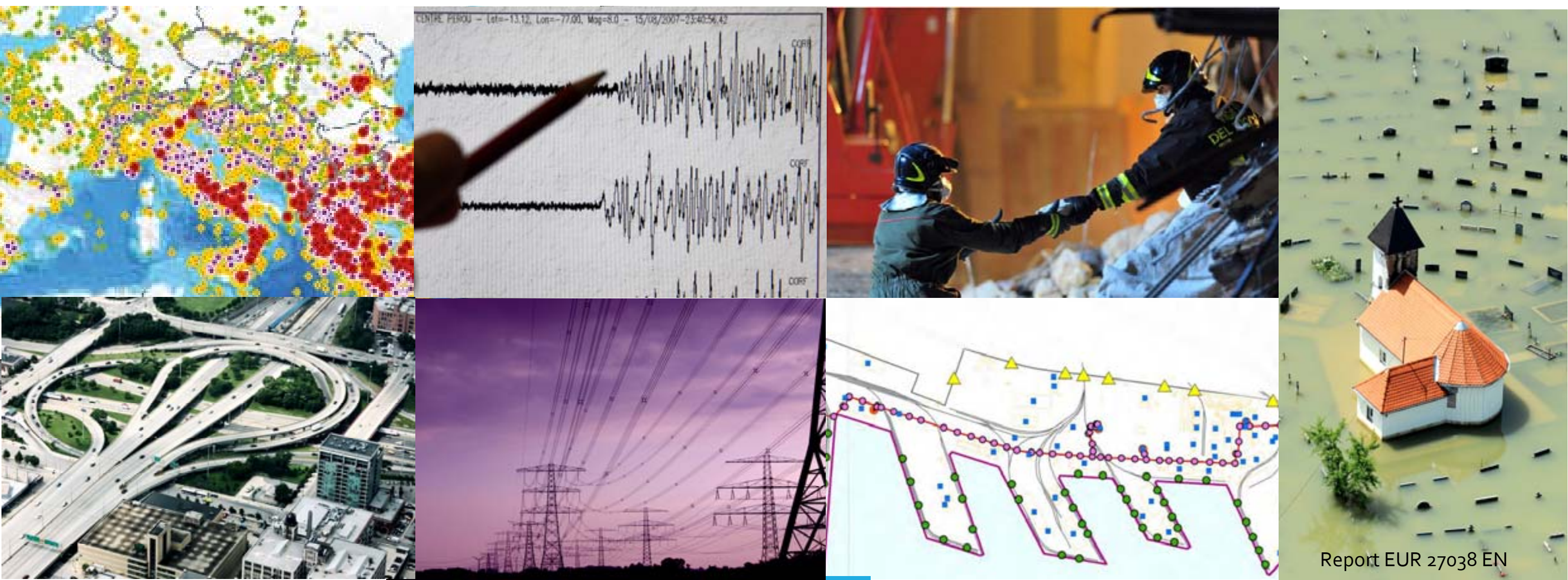

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Abstract

Resilience is a new approach in earthquake engineering that introduces the time dimension to cover the post-event recovery phase. It also broadens the scope beyond the single structure, to systems and communities. In the wider sense, resilience incorporates technical, organization, social, economic and environmental issues. The current goal of minimising casualties, economic and functionality loss, is extended to the requirement for the affected community or system to return to 'normal' conditions within the shortest possible time.
This report covers both conceptual and operational aspects of seismic resilience. It presents mathematical expressions used for the quantification of resilience, together with single- and multi-dimensional functionality measures for assets and systems. Moreover, it deals with interdependencies between systems, uncertainties, and multiple hazards and events.
In view of the establishment of a common methodology for resilience assessment, topics that need to be further investigated include the definition of boundaries in relation to space and time, the aspects to consider in resilience assessment, the collection and dissemination of data, the calibration of recovery functions on existing data and the validation of methods through application to real-life complex systems.

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Table of Contents

List of Figures

List of Tables

1 Introduction

Earthquake design aims at the limitation of damage for a frequent seismic event and at the protection of life and property for an event with lower probability of occurrence. However, several earthquakes that have hit densely populated areas or ones where significant economic activities were hosted, have shown that the consequences for the community may be disproportionate to the level of structural damage and that significant time and effort is necessary to regain pre-event conditions. This becomes critical if one considers extreme events of intensity beyond the values specified in design standards.

Resilience is a new approach in earthquake engineering that introduces the time dimension to cover the post-event recovery phase. It also extends the scope beyond the single structure, to systems and communities. In the broader sense, resilience incorporates technical, organization, social, economic and environmental issues. As pointed out by Ahern (2011), it shifts the design requirements from 'fail-safe' to 'safe-to-fail', in other words from a system that – at a prescribed level of disturbance – will not fail, to one where failure – probably at a higher level of disturbance – is acceptable and followed by a recovery phase, ideally at an optimal combination of time and cost. The current goal of minimising casualties, economic and functionality loss, is extended to the requirement for the affected community or system to return to 'normal' conditions within the shortest possible time (Manyena 2006).

The earliest policy drivers for disaster resilience may be traced at the framework adopted by the World Conference on Disaster Reduction that was organised by the United Nations. The outcome to pursue, namely '*the substantial reduction of disaster losses, in lives and in the social, economic and environmental assets of communities and countries*' (UN/ISDR 2005), introduces four aspects of resilience: safety, social, economic and environmental; it also sets communities and countries as the level at which to treat these aspects. The action framework calls for a multi-hazard approach and highlights the importance of the collection, analysis and dissemination of statistical data on disaster occurrence, impacts and losses, and of the exchange of information on good practices, risk reduction technologies and lessons learned. Furthermore, it acknowledges the role of building codes and standards in fostering disaster-resistant structures. There is explicit reference to critical facilities and infrastructures, such as schools, hospitals, water and power plants, communication and transport lifelines, management centres and structures of cultural significance.

At European level, increasing resilience to natural, human induced and conflict-related disasters was initially addressed by the EU external assistance activities. Recently, the UN/ISDR framework was extended to address a number of emerging challenges including, inter alia, the effects of climate change, energy demands, multi-risk events, highly frequent localised events and cross-border risks[1]. The proposed EU framework for implementation of

[1] The post 2015 Hyogo framework for action: managing risks to achieve resilience. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2014) 216 final, 8.4.2014, Brussels

a cross-sectorial disaster risk management policy promotes a holistic approach that covers all natural and man-made risks. It is also seen as a driver for innovation, growth and employment.

In the USA, a Proclamation by President Obama[2] set the goal to '*ensure a more resilient Nation – one in which individuals, communities, and our economy can adapt to changing conditions as well as withstand and rapidly recover from disruption due to emergencies*'. In the earthquake engineering community, the 2020 Vision for Earthquake Engineering Research identified several directions to follow, including metrics to quantify resilience, as well as monitoring and assessing resilience (Dyke et al 2010).

Being relatively new, the issue of seismic resilience has not yet been codified. Very recently, the draft building code of New Zealand (Mieler and Uma 2014) integrates in seismic performance objectives the impact of a damaged building on the community. It prescribes seven 'tolerable impact levels', related to performance requirements not only for life safety and physical damage, but also for loss of functionality and reparability. Threshold values are to be defined by the community, considering the collected data on the overall consequences of damage on buildings due to past events.

This report intends to cover both conceptual and operational aspects of seismic resilience. Section 2 deals with the conceptual framework of resilience, starting with a discussion of different definitions and extending to its properties, aspects and dimensions. It also covers strategies to improve the resilience of systems and communities. Section 3 presents a selection of mathematical expressions used in literature for the quantification of resilience, together with single and multi-dimensional functionality measures for a number of assets and systems. Moreover, it introduces the importance of accounting for interdependencies between systems. Section 4 is dedicated to the way uncertainties regarding the quantification of resilience may be addressed, while the formulation and metrics for resilience against multiple hazards and events is the object of Section 5. Some of the above topics, such as metrics for performance, interdependencies and multiple hazards, have been extensively investigated in the past in the context of risk assessment studies. In this report, the focus will be on the way they were treated in previous studies regarding resilience. The links between resilience and sustainability are investigated in Section 6. Finally, the main points of the state-of-the-art in seismic resilience are summarised and topics that need further development are put forward in Section 7.

[2] National preparedness month, Proclamation by the President of the United States of America, 4.9.2009

2 Conceptual framework

2.1 DEFINITION OF RESILIENCE

The term resilience has been used in disparate disciplines such as ecology, physics, psychology and psychiatrics before it was introduced in engineering and risk/disaster management (Manyena 2006). This results in inconsistent definitions, which is seen by many researchers as a major difficulty to overcome in the way of creating a harmonised and operational framework.

Following Gilbert (2010), the definitions of resilience fall into two categories: outcome-oriented and process-oriented. The former define resilience in terms of end results, such as percentage and time of recovery, and will be mainly discussed in the following. The latter are of interest mostly from the point of view of social sciences. Similarly, and depending on the system under consideration, Kahan et al (2009) differentiate between 'hard resilience', which relates to the structural, technical and mechanical qualities of institutions and infrastructure, and 'soft resilience', which deals with behaviours, psychology, relationships and endeavours of citizens and society.

Resilience is generally defined as the quality/ability of systems or communities to recover (or bounce back, or counterbalance, or adjust) following a disruptive event. In some cases, the definition includes the minimisation of initial loss and the recovery speed. The United Nations Office for Disaster Risk Reduction defines resilience as the capacity of a system, community or society potentially exposed to hazards to *adapt, by resisting or changing* in order to reach and maintain an acceptable level of functioning and structure (UN/ISDR 2005).

Focusing more on earthquake engineering, the research group of the Multidisciplinary Center for Earthquake Engineering Research defines resilience as the ability of a system to reduce the chances of a shock, to absorb a shock if it occurs and to recover quickly afterwards (Bruneau et al 2003). More specifically, a resilient system shows the following:

- reduced failure probabilities;
- reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences;
- reduced time to recovery (restoration to 'normal' performance).

The second property is termed 'inherent' or 'static' resilience and the third is referred to as 'adaptive' or 'dynamic' resilience (Paton and Johnston 2006, NRC 2011).

In a similar way, Bruneau et al (2003) define community seismic resilience as the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities so as to minimise social disruption and mitigate the effects of future earthquakes. The last point that refers to future events is an additional requirement for recovery, further discussed in Section 2.2.

It was anticipated that resilience planning is an extension of the current risk management and therefore requires new competences. This implies dealing with complexity, interdependency and boundaries (Kahan et al 2009). Complexity arises from the number of stakeholders involved and the portfolio of hazards to consider. Interdependency – possibly leading to cascade effects – stands for the impacts that damage of one system may have on the functioning of another, e.g. loss of electric power may hinder the water distribution system. Lastly, to remain feasible, resilience planning should set boundaries in the hazards, systems and geographic area examined as well as the resources available.

Manyena (2006) attempted a comparison between resilience and the current way of dealing with risk, i.e. aiming at reducing vulnerability. As shown in Table 2.1, the conventional objective has been to achieve safety through sufficient resistance, quantified by force. Resilience, on the other hand, sets the goal of bouncing back and measures the necessary time for recovery. The term adaptation is used instead of mitigation, meaning that some damage/loss is accepted but also that the system or community is expected to pass through a number of states during the recovery phase. In the same table, the contrast between engineering and culture is probably outdated, as engineering approaches are not limited to vulnerability, but have been extended to several aspects of resilience and for a number of assets and systems. As will be shown in the remaining parts of this report, comprehensive engineering approaches have been developed for resilience assessment of both individual structures and infrastructures. Relevant standards are not available yet, but sufficient knowledge has been acquired to support standardisation in the near future.

Table 2.1 Differences between vulnerability and resilience, adapted from Manyena (2006)

Vulnerability	Resilience
Resistance	Recovery
Safety	Bounce back
Force-bound	Time-bound
Mitigation	Adaptation
Institutional	Community-based
Risk assessment	Vulnerability and capacity analysis
Engineering	Culture
Standards	Institution

2.2 DEFINITION OF RECOVERY

Consideration of the recovery phase is the main step forward taken in resilience assessment. Following a disruption, functionality will remain at its residual value for the time necessary to mobilise resources and plan the required interventions (idle period). It will then start to increase as the planned measures will be implemented (recovery period). From the organisational point of view, the recovery phase may be divided in four periods: i) an initial response phase conducted by local resources while external resources are being mobilized; ii) an integration phase while external resources are incorporated into a functioning organization; iii) a production phase during which all resources are fully operative and deliver the requested services and iv) a demobilisation phase after recovery has been completed (Harrald 2006).

The procedure described above is represented by the continuous line in the functionality versus time curves plotted in Fig. 2.1. It might be decided to reach a higher or lower level of functionality compared to the initial one; these options are shown respectively by the dotted lines numbered 1 and 2. The dashed line 3 illustrates the case of a subsequent event, e.g. an aftershock that occurs during the recovery period. Finally, line 4 corresponds to the case that no action is taken to restore the functionality and the asset is left to degrade. For simplicity, a linear recovery path was assumed, but other paths are possible, as illustrated in Fig. 2.1(right). Depending on the initial damage, the availability of resources and the planning, recovery may start at a rapid pace that slows down when reaching the target functionality (curve a) or may progress slowly at the beginning and accelerate later on (curve b). More complex paths have been proposed, depending on the system and the response (Cimellaro et al 2010), or on the level of initial damage (Decò et al 2013).

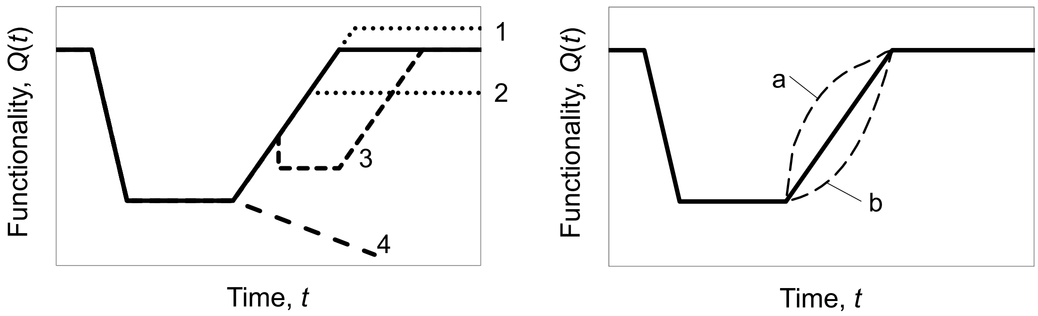

Fig. 2.1 Functionality versus time curves for different target functionalities (left) and recovery paths (light)

A simplification often adopted is to assume that the pre-disaster conditions are normal and static and therefore full recovery corresponds to return to the ex-ante state. This is referred to as 'before versus after' evaluation. It is more rational though, to consider the natural evolution of the system's quality over time and to consider that the system has fully recovered when it has reached a state as good as it would have attained had the disruptive event never occurred, e.g. NRC (2011). This is called a 'with versus without' comparison of functionality (Gilbert 2010). For example, in the particular case of ageing of precast concrete structures, studied by Titi and Biondini (2013), it was shown that functionality is reduced over time due to the corrosion of steel rebars and that lower values of resilience are calculated for the same earthquake occurring later during the life cycle. It is also argued that successful recovery should aim at more than 100 % of the pre-event functionality, particularly for assets, systems or communities that initially possessed insufficient functionality.

Historical evidence on cities hit by disasters of various nature, from the 13th century until the present day, shows that full recovery at the city level was achieved and that no long-term consequences were reported at national level (Gilbert 2010). A striking exception is the port of Kobe, which managed to recover only 10 % of its pre-earthquake container traffic. Models calibrated on real data are available in literature for the recovery of communities and lifelines struck by natural hazards. Examples include the distribution network for gas, electric power and water in the city of Sendai in Japan (Isumi et al 1985), the electricity network in North Carolina, South Carolina and Virginia for hurricane and ice storm hazards (Liu et al 2007), the highway network, population, business and economy after the Kobe earthquake (Chang and Nojima 2001, Chang 2010), and the community, electric power and telecommunications network following hurricane Katrina (Burton 2012, Reed et al 2009).

It is generally accepted, e.g. Dyke et al (2010), that the community should decide the desired time for recovery. By way of example, target states of recovery for buildings and infrastructure of San Francisco (SPUR 2009) are given in Fig. 2.2. Critical facilities should remain safe and operational immediately after the earthquake, or fully recover within the following four hours, while most essential services to citizens should remain safe and recover 90 % of the pre-event functionality in three days. Note, though, that complete recovery of all infrastructure is not expected before three years after the event.

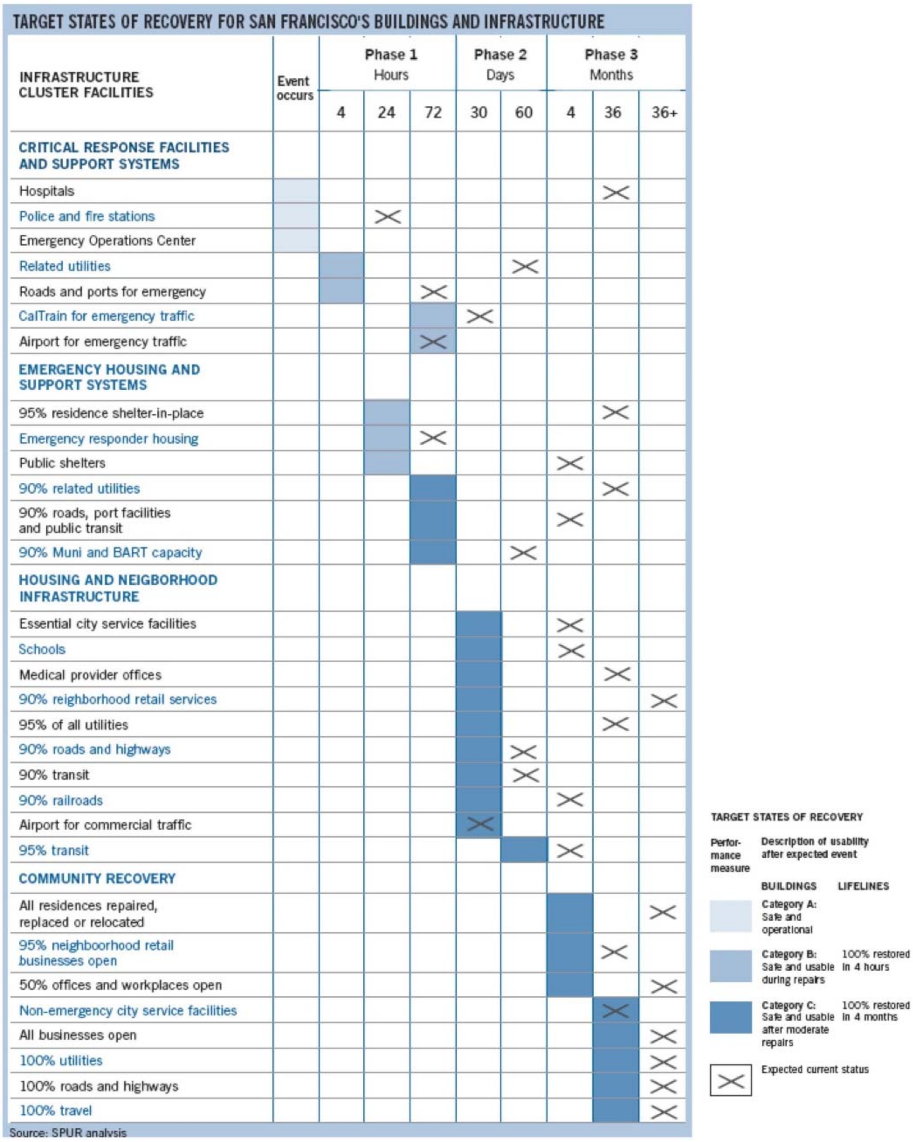

Fig. 2.2 Target states of recovery for San Francisco's buildings and infrastructure (SPUR 2009)

A recovery timescale that covers not only buildings and infrastructure, but also emergency response, health services, economy and the environment is given in Table 2.2 (NRC 2011). It comprises six time-scales, starting from the three days following the event. During this immediate response period, supply of food, water and power is critical to support the economy and the social system. The target for full recovery of all sectors is set at approximately one year. Beyond this period, resources should be used to integrate into the reconstruction effort and mitigation measures aiming to reduce losses from future events.

Table 2.2 Time scale for social, ecological, physical and economic recovery (NRC 2011)

Time scale	Emergency response	Health and safety	Utilities	Buildings	Environment	Economy
Immediate < 72 hours	Tactical emergency response	Deal with casualties, reunite families	Use of emergency backup systems	Remove debris	Limit further damage	Maintain supply of critical goods and services
Emergency 3-7 days	Strategic emergency response	Provide mass care	Begin service restoration	Provide shelter for homeless	Remove debris	Prioritise use of resources, substitute inputs, conserve
Very short 7-30 days	Selective response	Fight infectious outbreaks	Continue restoration	Provide shelter for homeless	Protect sensitive ecosystems	Shore up or over-ride markets
Short 1-6 months	Assist in recovery	Deal with post-traumatic stress	Complete service restoration	Provide temporary housing and business sites	Deal with ensuing problems	Cope with small business strain
Medium 6-12 months	Reassess for future emergencies	Deal with post-traumatic stress	Reassess for future emergencies	Provide temporary housing and business sites	Initiate remediation	Cope with large business strain, recapture loss production
Long > 1 year		Reassess for future emergencies	Mitigation for future events	Rebuild and mitigate	Mitigate for future events	Cope with business failures/mitigation

Table 2.3 Maximum values of target time for full recovery of critical services, utilities, transportation system, buildings and economic sectors in Washington state (RWS 2012)

Critical services	Time (days)	Utilities	Time (days)	Transportation	Time (days)	Buildings	Time (days)	Economy	Time (days)
Law enforcement	7	Domestic water	3	Bridges	3/90	Unreinforced masonry	365	Finance	30
Emergency response	3	Wastewater	30	Ferries	30	Pre-1950 single family houses	7**	Commerce	30
Health care	30	Flood control	30	Arterial roadways	30/365	Post-1950 single family houses	3**	Real estate	30
Education	30	Electricity	30	Airports	30	Pre-1977 mid- and high-rise structures	90**	Manufacturing	90
Mass care	7	Natural gas (distribution)	30	Ports	90	Post-1977 mid- and high-rise structures	30**		
Social services	30	Petroleum (distribution)	7	Railways	90				
Food network	30	ICT	7	Public transportation	90/365				
Government administration	7								

* depending on the location, ** 90 % of the stock is occupier

Recovery times for the state of Washington are given in Table 2.3, where maximum target values based on expert opinion are reported (RWS 2012). For critical services, utilities and transportation, the values in Table 2.3 refer to recovery to 80-90 % of the pre-event functionality. For the transportation system, buildings and economic sectors, three levels of recovery – minimal, functional and operational – are distinguished, each with increasing recovery times.

The resilience-based earthquake design initiative (REDi™) rating system, described by Almufti and Willford (2013), comprises three classes of buildings with increasing resilience: silver, gold and platinum. For each class, target values for occupancy, recovery time, direct economic loss (as percentage of total replacement value) and safety of occupants are given in Table 2.4 for the design earthquake.

Table 2.4 Resilience objectives for the design earthquake (Almufti and Willford 2013)

	Silver	Gold	Platinum
Occupancy	< 6 months	Immediate	Immediate
Functional recovery	< 6 months	< 1 month	< 72 hours
Direct financial loss	< 10 %	< 5 %	< 2.5 %
Physical injury of occupants	Possible	Unlikely	Unlikely

For practical applications, it must be kept in mind that the recovery time is a random variable with high uncertainties. It typically depends on the earthquake – or any other hazard – intensity, the type of area considered and the availability of human, economic and material resources such following the event (Cimellaro et al 2006a). A proportional coupling often (but not always) exists between the time to recovery and the initial loss of structural integrity. For example, cosmetic damage is easier to repair than severe damage to structural elements (Bruneau and Reinhorn 2007). A linear recovery function is generally used when there is no information regarding the response, while an exponential one is used where the response is initially very fast, driven by an initial inflow of resources, and the rapidity of recovery decreases in the following. Finally, a recovery path that follows a trigonometric function is used when the response to the perturbation is initially very slow initially, e.g. due to lack of organization and/or resources, but the rapidity of recovery increases subsequently, for example thanks to aid from outside the community/system (Cimellaro et al 2009).

2.3 PROPERTIES AND DIMENSIONS OF RESILIENCE

Having discussed the definition of resilience and recovery, a short description of the PEOPLES framework is given in the following. It is a holistic framework developed specifically for defining and measuring seismic resilience of communities at different scales. It covers several dimensions and properties of resilience – these two terms are given different meanings by various researchers, which is a further evidence of inconsistency. In the following, dimensions will refer to the sectors (e.g. technical, organisation, society and economy) for which resilience is evaluated, whereas properties will cover qualities or characteristics of assets and systems that are beneficial for resilience.

2.3.1 The PEOPLES framework

The PEOPLES framework (Renschler et al 2010) was developed for measuring the resilience of assets and classes thereof. It provides links between resilience properties and dimensions and integrates multiple hazards (natural, technical and cultural-social) over space and time. For critical infrastructures, mainly technological aspects are examined, while all dimensions are studied at community level. The framework covers the following:

- Population and demographics are assessed in terms of social vulnerability, which is the inherent inability of people, organizations and societies to withstand and recover from adverse impacts.
- Environmental and ecosystem resources measure the ability of the ecological system to return to the pre-event state.
- Organized governmental services include services like police, fire fighters and public health facilities.
- The physical infrastructure dimension focuses on the built environment and comprises facilities for housing, commercial and cultural use and lifelines. Lifelines include energy utilities (electric power, gas and fuel distribution networks), transportation systems (roads, highways, railroads, airports and ports), water and wastewater networks, communication systems and health care facilities.
- Lifestyle and community competence deals with collective action, flexibility, efficacy, empowerment and political partnerships.
- Economic development relates to the current economic activity of the community together with its ability to sustain economic growth.
- Social-cultural capital incorporates education, child and elderly services, cultural services and community participation. It also includes intangible goods, such as social support, sense of community, place attachment and citizen participation.

2.3.2 Properties of resilience

According to Bruneau et al (2003), resilience for physical and social systems consists of the ‘four R’s’ properties: robustness, redundancy, resourcefulness and rapidity. In detail:

- Robustness is the ability (strength) to withstand perturbations without degradation or loss of function, or the insensitivity to perturbations (Haimes 2009).
- Redundancy is the extent to which systems are capable of satisfying functional requirements following a disruptive event. In a redundant system, once a component fails, other components will assume the functions of the failed one.
- Resourcefulness is the capacity to identify problems, establish priorities and mobilise/apply material and human resources.
- Rapidity stands for meeting priorities in a timely manner, so as to limit losses and avoid future disruption. The term recoverability is also employed, e.g. by Barker et al (2013), for the speed at which an element or system recovers to a desired state.

Based on previous research, Godschalk (2003) collected a number of properties of resilient systems. Further to strength, redundancy and resourcefulness (also termed efficiency), they include:

- o diversity, which is the capacity of functionally different components to protect the system against various threats;
- o efficiency - with a positive ratio of energy supplied to energy delivered by a dynamic system;
- o autonomy, that characterises a system able to operate independently of outside control;
- o adaptability, referring to flexibility to change and learning from experience;
- o cooperativeness, promoting the participation of stakeholders by means of opportunities and incentives.

Francis and Bekera (2014) proposed a similar set of properties, where robustness and rapidity are respectively termed absorptive and restorative capacities. The latter relates not only to the pre-event functionality, but also to reliability. They further introduced the adaptive capacity, which is the ability of a system to adjust to undesirable situations.

Kahan et al (2009) developed a suite of principles to describe the essential concepts and assist in the design of resilience systems. As shown in Table 2.5, each principle contributes to one or more of the three objectives of resistance, absorption and restoration. Similarly to the framework discussed above, the principles include robustness, adaptability as well as comprehensiveness across space (local and regional level) and dimensions (social, economic, etc.). The control and containment of cascade events is introduced through the principle for consequence mitigation and is related to the restoration objective. The suite includes additional principles relative to the pre-event phase such as the attenuation of the damage potential of natural and human hazards, contributing to the resistance of the system, and the harmonisation of purposes across all principles. Finally, risk-informed planning and investment should consider three factors for systems and their functions: threat, vulnerability and consequence.

Table 2.5 Relationship between resilience objectives and principles (Kahan et al 2009)

	Objectives		
Principles	**Resistance**	**Absorption**	**Restoration**
Threat and hazard limitation	✓		
Robustness		✓	
Consequence mitigation			✓
Adaptability	✓	✓	✓
Risk-informed planning	✓	✓	✓
Risk-informed investments	✓	✓	✓
Harmonization of purposes	✓	✓	✓
Comprehensiveness of scope	✓	✓	✓

Godschalk (2003) and Kahan et al (2009) consider the beneficial aspect of interdependency, in the sense that interconnected components and systems will be able to support each other, on the condition that appropriate relationships have been planned and established. This is similar to redundancy and may apply across sectors, e.g. a robust economy may support some functions of the society. For the case of physical infrastructure, interdependency is normally considered a negative property that potentially leads to cascade effects.

2.3.3 Dimensions of resilience

Seismic resilience encompasses four interrelated dimensions: technical, organizational, social and economic (Bruneau et al 2003). The technical dimension refers to the ability of physical systems and their components to perform to acceptable levels when subject to earthquakes. The organizational dimension takes into account the capacity and rapidity of organizations that manage critical facilities, while the social dimension deals with the consequences on communities due to the loss of critical services. Lastly, the economic dimension refers to the capacity to reduce direct and indirect economic losses. Bruneau et al (2003) argue that there is no single measure for all four dimensions of community resilience and that different performance measures are required for each system under analysis.

The US National Research Council elaborated on these dimensions and proposed additional aspects to take into account (NRC 2011). It is first acknowledged that the concept of resilience is applicable at multiple scales, from the individual person to that of an organisation, neighbourhood, city or nation. In the technical dimension, it is suggested to consider both damage of stock, which occurs at a given point in time, and the disruption of the production of goods and services, which continues until the functionality of assets, system and communities is repristinated. As regards the organisational dimension, it is recognised that the recovery phase may not evolve as intended, as it will be influenced by the activities of private and public decision-makers. Then, an adaptive capacity is needed during the implementation of planned actions. Fairness, or equity, is introduced in the social dimension to focus on the needs of the most disadvantaged social groups. Finally, with reference to economy, it is suggested to include cost-benefit considerations in policy decisions.

2.3.4 Relation between properties and dimensions of resilience

The properties and dimensions of resilience are presented in Fig. 2.3, which also shows their relation. Robustness and rapidity are the desired ends and are achieved through appropriate measures to enhance resilience. They are also the main outcomes to communicate to decision-makers and stakeholders. On the other hand, redundancy and resourcefulness are seen as the means by which to improve resilience. The properties of diversity and autonomy are related to redundancy, while those of efficiency, adaptability and cooperativeness complement resourcefulness.

Redundancy and robustness make part of the technical dimension, which regards the performance of assets. Robustness is also related to the social and economic dimensions, as it concerns the effects of the disruptive event. Resourcefulness and rapidity are integrated in the organisational dimension. Rapidity stands for the recovery and therefore belongs also to the social dimension.

The technical dimension (ability to perform) has an impact on the social and economic consequences, or losses, of an event. The social dimension is also affected by the organisational one, as the latter reflects the capacity and rapidity of organizations that manage critical facilities. The economic dimension is limited to the direct and indirect losses; if it is taken to incorporate initial investment to increase resilience, it may also be considered to affect all dimensions. Structural engineers will probably tackle more easily the technical and economic dimensions. On the other hand, the social and economic dimensions have more complex interconnections and therefore will be more difficult to define and measure.

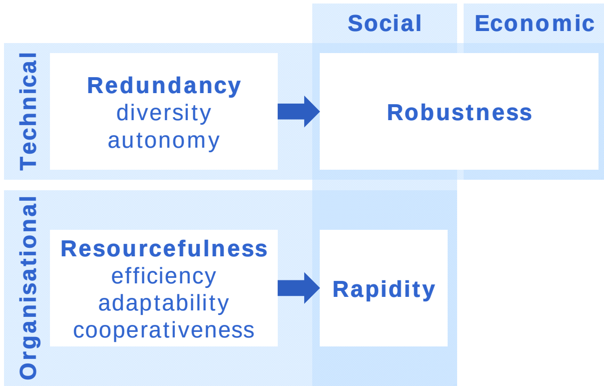

Fig. 2.3 Relation between properties and dimensions of resilience

2.4 MITIGATION STRATEGIES

In general, the objective of enhancing seismic resilience is to minimise the reduction in quality of life due to earthquakes (Bruneau et al 2003), focusing on organisations that provide essential functions in the aftermath of disasters. Such critical facilities include water and power lifelines, hospitals and local emergency management units.

To achieve this objective, Ahern (2011) proposed several strategies including multi-functionality, redundancy and modularisation, multi-scale connectivity, response diversity, and adaptive design. Multi-functionality is a higher-level property that is achieved through combining, stacking or time-shifting functions.

Redundancy – a familiar concept in earthquake engineering – and modularization intend to spread the risks among multiple components that provide the same or similar functions. In other words, it is seen as the ability of components to assume the functions of failed ones without adversely affecting the performance of the system itself (Haimes 2009). A special case is the presence of back-up systems that compensate for damaged elements (Cox et al 2011).

A similar strategy applied to networks is multi-scale connectivity or decoupling of systems. It aims at providing alternative supply routes, which may accommodate the flows and consequently maintain functionality following a disruptive event. Multi-scale connectivity is low in local networks or in cases where damage is spatially distributed in a large area.

Response diversity originates from the environmental sciences and refers to components that have similar functions and different response to disturbance. Relevant concepts in seismic design of structures are capacity design (preference of ductile over brittle response of bearing elements) and the classification of elements as primary and secondary (contributing to seismic resistance or carrying only vertical loads).

Adaptive planning and design implies monitoring and analysis of the system, similar to current applications for the structural health and functionality of some critical infrastructures and lifelines.

Almufti and Willford (2013) list a number of measures that aim to increase the seismic resilience of buildings, mainly by removing obstacles and speeding the recovery process. Back-up and redundant utility systems for electricity, gas, water and wastewater will minimise the consequences of damage to the local distribution networks. Higher resilience, at a higher cost, may be achieved using off-grid technologies, which allow the buildings to continue to function without the support of the local utility grid. For instance, rainwater harvesting, on-site wells and other natural closed-loop systems may provide water, whereas on-site renewable energy generators may supply power. On the organisational aspect of resilience, it is advantageous to plan beforehand for the financial and human resources necessary for damage assessment, design and implementation of retrofit measures.

3 Measuring resilience

3.1 QUANTIFICATION OF RESILIENCE

As for the conceptual level, there are several proposals in literature for the quantitative estimation of resilience. They all make use of a plot of functionality versus time, as the one shown in Fig. 3.1. The disruptive event occurs at time t_0 and the pre-event functionality is usually taken $Q(t_0)$ = 100 %. Following the event, functionality is gradually reduced until its minimum, or residual, value $Q(t_d)$ and maintains that value until recovery operations initiate at time t_i. For a seismic event and without influence from other systems, t_d will probably coincide with t_0; in other words, the system will reach the lowest functionality level immediately after the event. Full recovery is achieved at time t_r. For simplicity, in Fig. 3.1 recovery is assumed to follow a linear path and to lead to the same quality as before the event.

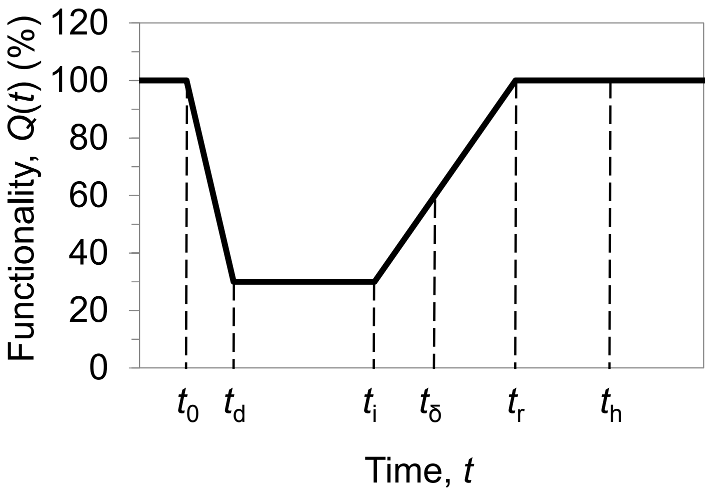

Fig. 3.1 Functionality versus time and characteristic times

Resilience at time *t* may be defined as the time-dependent ratio of recovery over loss (e.g. Barker et al 2013, Henry and Ramirez-Marquez 2012). By denoting $Q(t)$ the functionality, or quality, of the system, resilience may be written as:

$$R(t) = \frac{Q(t) - Q(t_d)}{Q(t_0) - Q(t_d)} \tag{1}$$

A similar expression of resilience computed as the ratio of functionalities was proposed by Francis and Bekera (2014):

$$R = S_p \frac{Q(t_r)Q(t_d)}{Q^2(t_0)} \tag{2}$$

where S_p is a speed recovery factor:

$$S_p = t_\delta / t_r^*, \text{ for } t_r < t_r^* \quad (3)$$

$$S_p = (t_\delta / t_r^*)\, e^{-\alpha(t_r - t_r^*)}, \text{ for } t_r \geq t_r^* \quad (4)$$

t_r^* is the time necessary to complete the initial recovery actions and *α* is a parameter controlling decay in resilience. Eqs. (2) - (4) introduce an intermediate control time, t_δ, when it is desired to have recovered a given percentage of functionality. Then, the value of *R* is adjusted depending on whether $Q(t_\delta)$ has been reached or not at t_δ.

The concept of the 'resilience triangle' has been introduced earlier (Bruneau et al 2003) to describe the area above the functionality curve, from the time of occurrence of the event until full recovery of functionality. Then, the loss of resilience is measured as:

$$R' = \int_{t_0}^{t_r} \left[100 - Q(t)\right] \partial t \quad (5)$$

An alternative definition of resilience (e.g. Bruneau and Reinhorn 2007) is the area below the functionality curve measured from t_0 until full recovery at t_r:

$$R = \int_{t_0}^{t_r} Q(t)\, \partial t \quad (6)$$

The so-computed values of resilience are measured in time units. Eq. (6) has the disadvantage that it will yield a lower value of resilience for faster recovery, which appears contradictory. For this reason, the following expression has been proposed (e.g. Bocchini and Frangopol 2011, Cimellaro et al 2009):

$$R = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} Q(t) \partial t \quad (7)$$

where the integral extends to a sufficiently large period of time t_h after full recovery, so that faster recovery will correspond to higher *R*-values. After dividing the integral by $t_h - t_d$, resilience becomes non-dimensional.

Based on Eq. (7), Cimellaro et al (2010) developed a methodology for resilience assessment of hospitals, which may be generalised to any asset or system. Functionality is defined as:

$$Q(t) = \left[1 - L(I, t_r)\right]\left[H(t - t_0) - H(t - t_r)\right] f_{\mathrm{R}}(t, t_0, t_r) \quad (8)$$

In the previous equation, $L(I,t_r)$ is the loss function following a disruptive event of intensity *I* and *H* is the Heaviside function. The appropriate form of the recovery function, $f_R(t,t_0,t_r)$, is selected on the basis of the system characteristics.

Losses consist of direct economic losses and casualties, respectively L_{DE} and L_{DC}, and indirect economic losses and casualties, respectively L_{IE} and L_{IC}. Direct economic losses are due to structural and non-structural damage and can be expressed as the ratio of building repair cost to replacement cost:

$$L_{DE}(I) = \sum_{j=1}^{n} \left(\frac{C_{S,j}}{I_S} \prod_{i=1}^{T_i} \frac{1 + \delta_i}{1 + r_i} \right) P_j \quad (9)$$

$C_{s,j}$ is the repair cost associated with damage state j, I_s is the replacement cost, T_i is the period of time between the initial investment and the occurrence of the event, δ_i is the annual depreciation rate, r_i is the annual discount rate and P_j is the fragility function, or the probability of exceeding a performance limit state j for an event of intensity I.

Total direct economic losses $L_{DE}(I)$ are calculated as:

$$L_{DE}(I) = \frac{1}{N}\sum_{k=1}^{N} w_k L_{DE,k}(I) \tag{10}$$

where N is the total number of structural and non-structural components, w_k is a weight factor associated with each building component and $L_{DE,k}(I)$ is the direct economic loss associated with the k-th component.

Direct casualties $L_{DC}(I)$ are measured as a ratio of the (instantaneous) number of injured or dead, N^1_{in}, and the total population, N_{tot}, of the examined area:

$$L_{DC}(I) = N^1_{in} / N_{tot} \tag{11}$$

Similarly, indirect casualties are

$$L_{IC}(I) = N_{in} / N_{tot} \tag{12}$$

where N_{in} is the number of people that are injured or die as a consequence of the reduced functionality of the system/community under study.

Finally, the total losses can be expressed as a weighted sum of direct and indirect losses:

$$L(I,t) = L_D(I) + \alpha_I L_I(I,t_r) \tag{13}$$

where α_I is a weighting factor that measures the importance of the examined facility for the community, the influence of the facility on other systems, etc. Direct and indirect losses may be calculated as follows:

$$L_D = \alpha_{DE} L_{DE}(1 + \alpha_{DC} L_{DC}) \tag{14}$$

$$L_I = \alpha_{IE} L_{IE}(1 + \alpha_{IC} L_{IC}) \tag{15}$$

In Eqs. (14) and (15), α_{DE} and α_{IE}, are weight factors related respectively to construction losses in economic terms and to business interruption, relocation expenses, rental income losses, etc. Finally, α_{DC} and α_{IC} are weight factors related to the nature of occupancy (i.e. schools, critical facilities, density of population). These factors are determined on the basis of socio-political considerations and require the collaboration of experts from different sciences.

Ouyang et al (2012) and Zobel (2011) proposed a different formulation for resilience defined as the area below the functionality curve, measured until t_h. Considering for simplicity $t_d = t_i = t_0$ and full recovery to the pre-event functionality, the analytical expression for resilience is:

$$R = \frac{T^* - XT/2}{T^*} = 1 - \frac{XT}{2T^*} \tag{16}$$

where $T = t_r - t_0$ is the time to recovery, $T^* = t_h - t_0$ is the period of time extending after recovery for which resilience is measured and $X = 1 - Q(t_d)$ is the initial loss of functionality.

Consider now two cases: A % loss of functionality recovered in B time-units and B % loss recovered in A time-units. For the analytical formulations of Eqs. (6), (7) and (16), the resilience is the same, but different stakeholders might prefer one or the other option depending on their priorities. It is then a political/social decision to define the desired balance between functionality and recovery time. It is argued, e.g. by Bruneau and Reinhorn (2007), that smaller initial loss will require shorter recovery time. This appears rational for many cases, but may not be true, for instance, when considering interdependent systems and cascade effects.

To assist in such a decision, Eq. (16) may be plotted in a graph of recovery time versus loss of functionality, as the one shown in Fig. 3.2, where a value of T^* has been assumed and the different curves correspond to different values of resilience. The owner/manager of the asset may define limit values for the initial loss and recovery time $\hat{X}$ and $\hat{T}$. These limit values, shown respectively by the bold vertical and horizontal lines, divide the plot in four regions. Region 1 represents the optimum combination of loss and recovery time, whereas regions 2 and 3 correspond respectively to short recovery time and low initial loss of functionality. Region 4 corresponds to solutions that exceed the prescribed limits of loss and recovery time. Such a plot serves also to visualise different events or assets and strategies for improvement of their resilience.

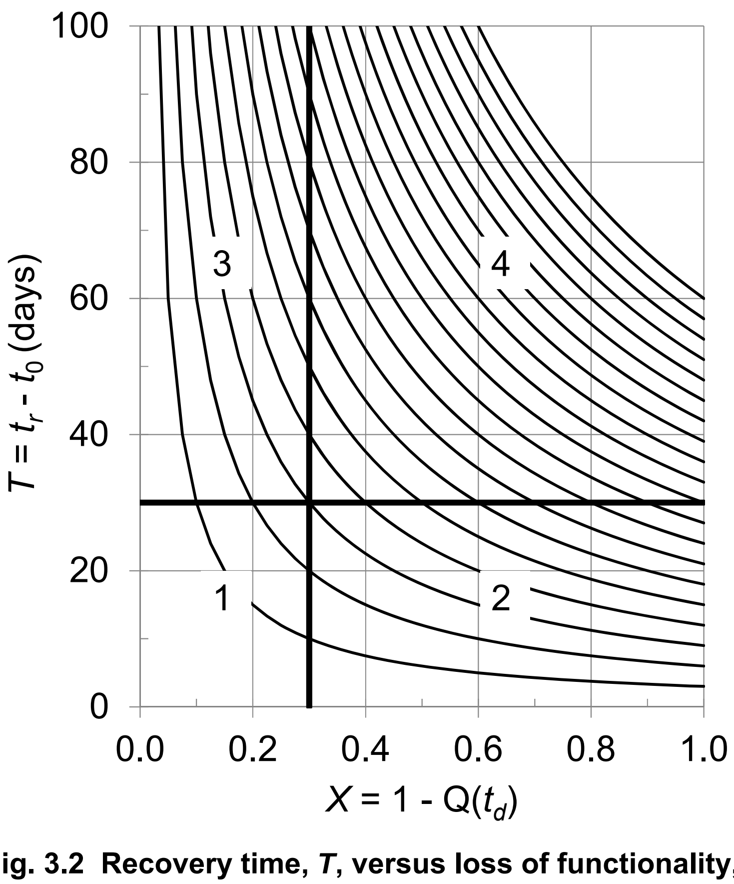

Fig. 3.2 Recovery time, *T*, versus loss of functionality, *X*

Zobel (2011) developed a procedure that permits to adjust Eq. (16) to the decision maker's perception of resilience by means of three parameters, α, γ and δ. For the four regions delimited in Fig. 3.2, resilience is calculated as:

$$R = 1 - \frac{(1-\alpha)XT}{2T^*} \quad \text{in region 1} \tag{17}$$

$$R = 1 - \frac{(1-\alpha)T\left[X + \delta(X - \hat{X})\right]}{2T^*} \quad \text{in region 2} \tag{18}$$

$$R = 1 - \frac{(1-\alpha)X\left[T + \gamma(T - \hat{T})\right]}{2T^*} \quad \text{in region 3} \tag{19}$$

$$R = 1 - \frac{(1-\alpha)\left[XT + \delta T(X - \hat{X}) + \gamma X(T - \hat{T})\right]}{2T^*} \quad \text{in region 4} \tag{20}$$

The decision maker is asked to express his/her estimation of resilience for a number of cases defined by specific pairs of X and T and then Eqs (17) to (20) are used to calculate the values of α, γ and δ that adjust resilience to the decision maker's priorities.

Fig. 3.3 illustrates the basis for the mathematical expressions of resilience that were previously discussed. Eq. (1) adopts a time-dependent definition as the fraction of initial loss that has been recovered, while Eq. (5) measures the loss of resilience as the area above the functionality curve. Finally, Eqs. (6) and (7) make use of the area below the functionality curve and provide non-dimensional values. The latter is the most commonly used for the assessment of the seismic resilience of structures, lifelines and transportation networks.

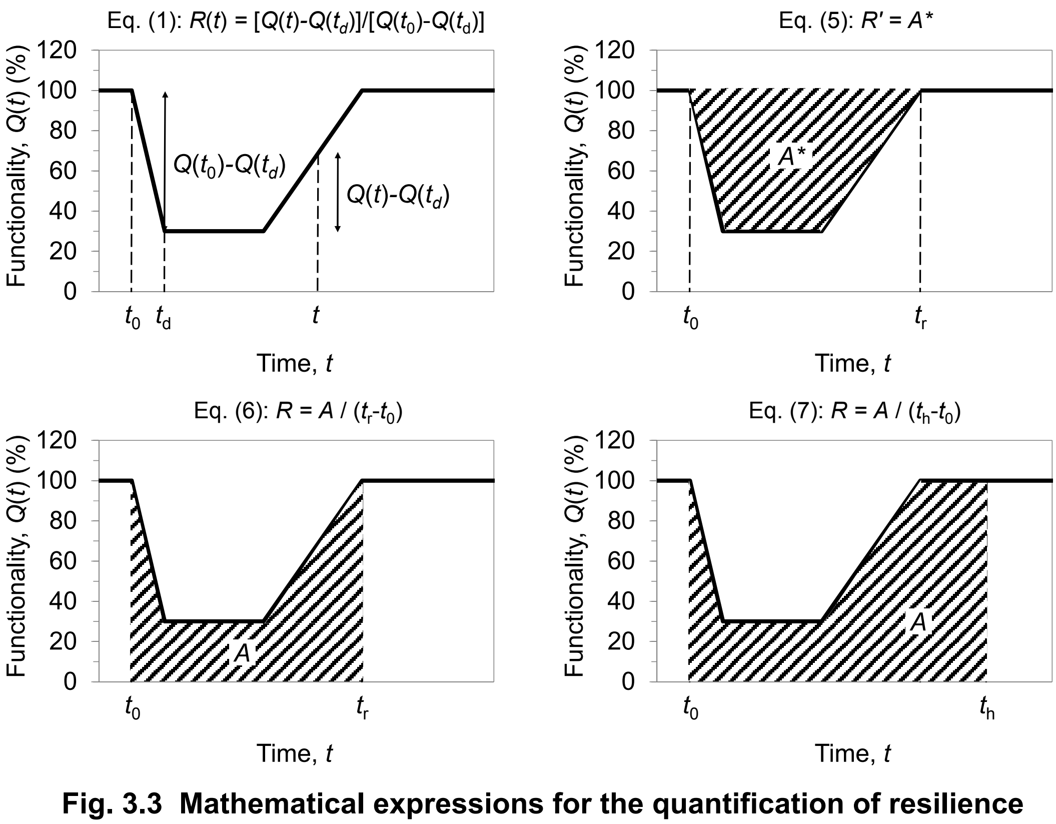

Fig. 3.3 Mathematical expressions for the quantification of resilience

3.2 FUNCTIONALITY METRICS

3.2.1 General

As discussed in 3.1, resilience is quantified with reference to a plot of functionality versus time. Metrics for the functionality of assets and systems are collected in this section, based on a review of the available literature. The terms ‘measure’ and ‘indicator’ are also used, the latter referring mainly to qualitative characteristics – e.g. employment, income, level of education and health of population, quality of housing and infrastructure, availability of shelters – that facilitate recovery. Also regarding metrics, there is lack of consensus on the most representative one. Therefore, multi-dimensional metrics are examined in 3.3. Table 3.1 presents a summary of functionality metrics and details are given in the following.

Table 3.1 Summary of functionality metrics for assets and systems

Asset / system	Functionality metrics
Lifelines	% of population with service % of functioning components / distribution lines % of time the service is delivered consumption per capita flow
Transportation network	% of nodes/edges open to traffic travel time queue length / time traffic flow journeys performed by other means number of changes between lines cost / number of shipments
Bridge	traffic volume number of open lanes maximum vehicle weight
Hospital	% of healthy population pre-hospital time waiting time patients treated per day
Economy	gross regional product damage to natural, human and human-made capital damage to monuments interruption of production processes
Society	casualties social disruption provision of essential services

Three criteria were proposed by Chang (2010) for the selection of measures. First, their definition should be meaningful and consistent across regions and time. Then, relevant data should be regularly collected and made available and lastly, there should be a standard measuring method. Measures that satisfy the above criteria are deemed appropriate for making comparisons. It is felt that the greatest obstacle is the availability of data, which is either not collected in a consistent way, or is not disclosed by the authorities that own and manage the assets. Three criteria for selecting resilience indicators were also used by Burton (2012). An indicator is first considered relevant, if this is sufficiently justified in literature. The second criterion refers again to the availability and quality of data and the third is more practical and requires indicators to be scalable. The first two criteria were also used by Cutter et al (2010) for the development of composite metrics.

Jordan and Javernick-Will (2012) reviewed over 200 journal articles aiming to identify the recovery indicators cited by authors working on different disciplines. Recovery indicators are defined as items that may be measured or assessed (either quantitatively or qualitatively) in order to determine whether a community has recovered and may be considered as functionality metrics. The information reported in Table 3.2 shows a selection of indicators that are deemed more representative by engineers, practitioners and inter-disciplinary researchers as regards the social, economic, environmental and infra-structural dimensions of resilience. The values in bold specify the most cited indicator by discipline. Overall, there is some degree of agreement among authors from different disciplines. For engineers in particular, the most quoted measures are population return, number of businesses, sustainability, and lifelines.

Table 3.2 Percentage of articles citing recovery indicators by author discipline, adapted from Jordan and Javernick-Will (2012)

Dimension	Measure	Engineer	Inter-disciplinary	Practitioner	All
Social	Equity	3.9	**10.7**	20.0	7.4
	Population return	**7.8**	3.6	**20.0**	**11.4**
	Quality of life	5.9	7.0	0.0	6.4
	Social services	5.9	3.6	0.0	5.0
Economic	Employment	2.9	10.7	0.0	7.9
	GNP	3.9	10.7	0.0	3.5
	Government revenue	1.0	0.0	0.0	0.5
	Income	2.9	**14.3**	20.0	7.4
	Housing values	1.0	0.0	0.0	0.5
	Nb. businesses	**5.9**	10.7	10.	**8.9**
	Standard of living	0.0	4.0	0.0	2.0
Environment	Air quality	2.0	0.0	0.0	1.0
	Erosion	1.0	**7.1**	10.0	2.0
	Land degradation	0.0	0.0	10.0	1.5
	Sustainability	**3.9**	**7.1**	**20.0**	**5.9**
	Water quality	2.0	0.0	0.0	1.5
Infra-structure	Debris removal	3.9	7.1	10.0	4.5
	Housing	15.7	**21.4**	**30.0**	**19.3**
	Facilities and lifelines	**21.6**	17.9	20.0	18.3
	Transportation	12.7	**21.4**	0.0	11.9
	Risk reduction	6.9	7.1	10.0	8.4

3.2.2 Networks

Lifelines and transportation systems are essentially networks made up of nodes and edges. Metrics for networks have been developed on the basis of the topological features, or combining topology and flow. Network functionality metrics include:

- o the maximum admissible number of failed nodes or edges so that the system maintains its pre-event function (Najjar and Gaudiot 1990, Rosenkrantz et al 2009);
- o characteristic path length, defined as the mean of the means of the shortest path lengths connecting each edge to all other edges (Dueñas-Osorio et al 2007). The concept of connectivity loss is useful to quantify the average decrease of the ability of distribution vertices to receive flow from the generation vertices. In other words, it quantifies the decrease in the number of generators connected to a distribution vertex.
- o path length or flow between two control nodes (Henry and Ramirez-Marques 2012);
- o ratio of usable path length to the total path length (Henry and Ramirez-Marques 2012);
- o sum of the node states, where the state of a node equals 0 if the node is not functioning and 1 if it is in function (Filippini and Silva 2014).

When examining a system, it is possible to estimate the importance of components making use of component importance measures, such as those proposed by Barker et al (2013). The first measure is the ratio of the system functionality loss due to failure of a component to the maximum loss among all components, multiplied by the time required to restore the original functionality. The second is called the ‘resilience worth’ and is measured by the normalised reduction of time to total system recovery in case a component suffers zero functionality loss. These measures allow identifying the components that produce the highest loss of system functionality, as well as those that contribute to resilience soon after the disruptive event, thus allowing to prioritise interventions.

3.2.3 Lifelines

Lifelines comprise the networks for distribution of water, electric power, natural gas and the telecommunications network. The most common metrics used in previous resilience studies are (Chang and Shinozuka 2004, Cimellaro et al 2011b, Milman and Short 2008, Ouyang et al 2012):

- o percentage of households, or number of people, with service;
- o percentage of functioning components (pumping stations, processing stations, tanks, etc.);
- o percentage, or length, of undamaged distribution lines;
- o per capita consumption;
- o portion of time the supply points are functioning;
- o amount of flow delivered.

3.2.4 Transportation networks

Transportation networks, i.e. highways, regional and local roads, railways, ports and airports, are vital for the everyday life of people, for the economy and even more for the transportation of victims, rescue teams and supplies during the post-event emergency phase. The focus of existing resilience studies has been on highways and railways and therefore only functionality metrics for these networks will be presented in the following.

Performance measures are mainly based on travelling time and speed, available nodes and shipment of goods (Arcidiacono et al 2012, Cimellaro et al 2011b, Cox et al 2011, Dorbritz 2011, Murray-Tuite 2006, Vugrin et al 2010). In detail, metrics retrieved from literature are:

- travel time between two specific nodes – the nodes may be selected to represent a zone with significant damage due to the event and one from where aid will depart or to where victims need to be transferred;
- shortest path length between nodes;
- percentage of network length or edges that are open to traffic;
- traffic flow;
- queue length (in number of vehicles) on a directed edge;
- queue time per vehicle;
- amount of time during which the average speed in a road segment is lower than a threshold;
- number of journeys performed by alternative transportation modes;
- number of changes between lines;
- number of served railway stations in the regional and the national networks;
- average cost of shipments;
- number of disrupted shipments.

3.2.5 Bridges

Bridges are critical components of highway and railway networks. Their functionality has been the object of research aiming at the mitigation of the seismic risk, before specific resilience studies were performed. Mackie and Stojadinović (2006) defined the functionality of a bridge in terms of lateral and vertical load-carrying capacity. Structural capacity was related to the traffic capacity of the bridge and its functionality, as shown in Table 3.3.

Table 3.3 Definition of bridge functionality levels (Mackie and Stojadinović 2006)

Operating conditions	**Remaining traffic capacity (%)**	**Loss of lateral load-carrying capacity (%)**	**Loss of vertical load-carrying capacity (%)**
Immediate access	100	< 2	< 5
Weight restriction	75	< 5	< 20
One lane open only	50	< 15	< 35
Emergency access only	25	< 25	< 50
Closed	0	> 25	> 50

Padgett and DesRoches (2007) used data collected from experts to relate bridge functionality to physical damage of its components. Results were presented as step-wise restoration curves for several levels of initial damage. As shown in Fig. 3.4(left), moderate damage produces total loss of functionality, which is restored to 50 % in one day and to 100 % in one week. Similarly, a bridge that suffers extensive damage will regain 50 % of its traffic carrying capacity in seven days and will fully recover in more than a month.

Based on observed data from California, HAZUS (FEMA 2010) provides restoration curves for highway bridges, as shown in Fig. 3.4(right). They give the percentage of functionality of a bridge that suffered a given damage level as a function of time following the seismic event. For example, a bridge with moderate damage is expected to be fully functional after approximately 10 days, whereas more than 3 months will be needed to fully restore the functionality of a bridge with extensive damage. The two sets of restoration curves shown in Fig. 3.4 are grossly in agreement.

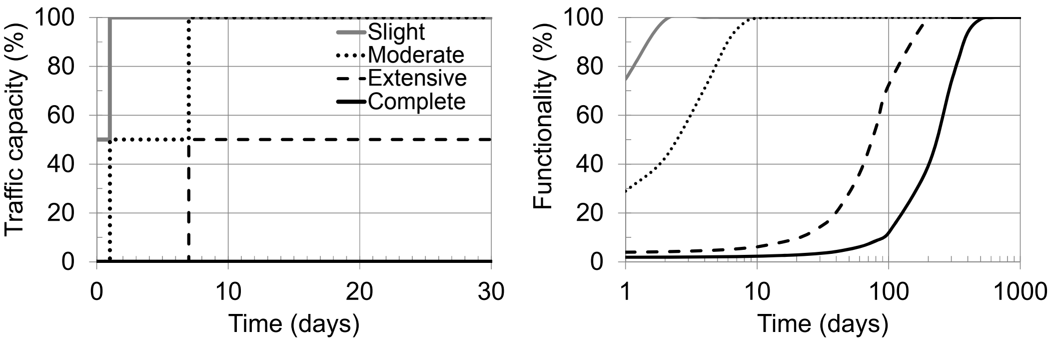

Fig. 3.4 Restoration curves for bridges: (left) based on expert opinion (Padgett and DesRoches 2007) and (right) based on observed data (FEMA 2010)

3.2.6 Hospitals

Several studies were dedicated to the performance and resilience assessment of hospitals and systems of hospitals (Bruneau and Reinhorn 2007, Cimellaro et al 2011a, Di Bartolomeo et al 2007). The functionality metrics employed include:

- o the percentage of healthy population, a global measure of community resilience;
- o the pre-hospital time, defined as the time elapsed from the emergency call to arrival at the hospital and depending on the accessibility to the hospital following the event;
- o the number of patients that can be treated per day;
- o the waiting time, which is the time that the patient needs to wait in the hospital before receiving treatment.

The calculation of the two last metrics requires an ad-hoc assessment of the damage state of all components to be performed for each hospital, possibly including interdependencies. For an accurate assessment, it is necessary to harmonise performance levels for structural and non-structural components and also to develop fragility curves for equipment.

3.2.7 Economy

The most straightforward measure for economic performance is the gross regional product, assuming that resilience is measured at regional level. Economic damages will have to be evaluated accounting for both direct, e.g. casualties, and indirect losses, e.g. disruption of industrial production because of electric power shortage. Howe and Cochrane (1993) developed a framework for measuring economic damage from natural hazards, which is made up of six elements:

1. damage to human-made capital;
2. interruptions of production processes;
3. identification of economic activities to be monitored over time;
4. damage to historical monuments and assets;
5. damage to human capital;
6. damage to natural capital, such as rivers, lakes, forests, etc.

The framework includes recommendations for the calculation of the economic loss, depending on the extent of damage and the action the owner decides to take. By way of example, the economic loss for a collapsed building is its market value, if it will be replaced, or the present value of income loss for the remaining service life, if it will not be replaced. For a damaged building that will be retrofitted, the loss is the rehabilitation cost, while for a damaged building that will not be retrofitted, the cost is the present value of income losses for its remaining service life. For the practical application of this framework, caution is needed where market prices diverge from the value given to assets by the society.

3.2.8 Society

Functionality from the social point of view – or better, quality of life – is difficult to quantify, as it practically depends on all of the other sectors. Bruneau et al (2003) list a number of qualitative social performance measures, including, among others, the avoidance of casualties and social disruption, the provision of essential services (health care, food, water, electricity) and the availability of water for fire-fighting. Some of these measures may be quantified as discussed previously, e.g. for hospitals and lifelines.

FEMA (2003) developed a set of guidelines for disaster-resilient universities, seen as a particular type of community. Their specific functionality may be measured through the instructional time, research equipment and library collections that are available following the disruptive event. In addition, there is the impact that the interruption of a higher education institution activities' will have on the local economy.

3.3 MULTI-DIMENSIONAL METRICS FOR RESILIENCE AND FUNCTIONALITY

As discussed in 3.2, there are several functionality metrics used in literature for different assets and systems, however, there is no consensus about the most appropriate one. In addition, metrics for the different aspects or dimensions of resilience need to be combined in some way to yield a global value of resilience at regional or community level. These two issues may be addressed by means of multi-dimensional metrics, as described in the following.

A two-dimensional limit state, combining floor acceleration and inter-storey drift, was examined by Bruneau and Reinhorn (2007) for the performance of structural and non-structural components of a hospital in the context of quantification of resilience. Setting respectively α_{LIM} and d_{LIM} as the acceleration and displacement limit thresholds, the probability of exceeding the limit state is:

$$P_{LS} = \lim_{N_{TE}\to\infty}\left\{\frac{N_R}{N_{TE}}\max\left[\left(\frac{R_\alpha}{\alpha_{LIM}}\right)^{N_a}+\left(\frac{R_d}{d_{LIM}}\right)^{N_d},1\right]\right\} \tag{21}$$

N_R is the number of responses that exceeds the performance limit, N_{TE} is total number of possible responses during the life cycle of the structure, R_a and R_d are the maximum acceleration and displacement responses and N_a and N_d are factors that define the shape of the limit surface.

Cutter et al (2010) in their work on composite resilience indicators proposed a methodology for the selection and weighting of measures, which may be useful for the development of multi-dimensional performance metrics. For ease of comparison, variables were transformed to non-dimensional form. The number of variables was then reduced by eliminating those variables that showed a high correlation with others. The values of variables related to each aspect of resilience (structural, economic, etc.) were averaged and subsequently these average values were summed to produce a global resilience value. Weighting factors may be applied in case sufficient justification is available. Arcidiacono et al (2012) also expressed the resilience of a system as the weighted sum of the sub-systems' resilience. Weights are based on expert judgement and further to the relative importance of each sub-system, they may also account for the importance of a specific asset with respect to other assets in the same sub-system.

Renschler et al (2010) proposed to compute the global functionality, Q_{tot}, of a community as a combination of the functionalities of different dimensions, based on the analogy with the probability axiom of arbitrary events:

$$Q_{tot} = \sum_{j=1}^{n} Q_j - \sum_{i=1}^{n}\sum_{j=2}^{n} Q_i Q_j + \sum_{i=1}^{n}\sum_{j=2}^{n}\sum_{k=3}^{n} Q_i Q_j Q_k - \ldots + (-1)^{n-1}\sum_{i=1}^{n}\sum_{j=2}^{n}\sum_{k=3}^{n}\ldots\sum_{l=n-1}^{n} Q_i Q_j Q_k \ldots Q_l Q_n \tag{22}$$

For the common case of dimensions with different weights, the global functionality can be determined as:

$$Q_{tot} = \sum_{i=1}^{n} p_i\left(r,t\right) Q_i\left(r,t\right) \tag{23}$$

where n is the number of dimensions considered relevant for the total functionality, $p_i(r,t)$ are priority factors, Q_i is the functionality associated with a given dimension and r is a matrix describing the area of interest.

Cimellaro et al (2011a) developed mathematical expressions for the time-dependent total functionality of a hospital, $Q(t)$, as the product of the qualitative, Q_{QS}, and quantitative, Q_{LS}, functionalities:

$$Q(t) = Q_{QS}(t)\ Q_{LS}(t) \tag{24}$$

Qualitative functionality is measured using the waiting time, WT, spent by people before they receive the required treatment. It is the weighted sum of two quantities:

$$Q_{QS}(t) = (1 - \alpha)\, Q_{QS,1}(t) + \alpha\, Q_{QS,2}(t) \tag{25}$$

$$Q_{QS,1}(t) = \frac{\max\left((WT_{crit} - WT(t)), 0\right)}{WT_{crit}} \text{ for } \lambda(t) \le \lambda_u \tag{26}$$

$$Q_{QS,2}(t) = \frac{WT_{crit}}{\max\left(WT_{crit}, WT(t)\right)} \qquad \text{for } \lambda(t) > \lambda_u \tag{27}$$

where α is a weighting factor for the combination of non-saturated and saturated conditions, $\lambda(t)$ is the arrival rate of patients at the hospital, λ_u and WT_{crit} are respectively the critical arrival rate of patients and the waiting time at saturated conditions. Saturated conditions correspond to achievement of the maximum capacity of the hospital.

Quantitative functionality $Q_{LS}(t)$ is defined as the number of treated patients to the total number of patients:

$$Q_{LS}(t) = 1 - \frac{N_{NTR}(t)}{N_{tot}(t)} \tag{28}$$

where $N_{tot}(t)$ is the total number of patients that require care after the event:

$$N_{tot}(t) = \int_{t_0}^{t_0+t} \lambda(\tau)\partial\tau \tag{29}$$

and N_{NTR} is the total number of patients that do not receive treatment:

$$N_{NTR}(t) = N_{tot}(t) - \int_{t_0}^{t_0+t} \min\left(\lambda(\tau), \lambda_u\right)\partial\tau \tag{30}$$

According to the previous equations, a hospital is fully functional in qualitative terms when it treats patients with a minimum delay, and in quantitative terms when it is able to treat all the patients it receives.

3.4 INTERDEPENDENCIES BETWEEN SYSTEMS

3.4.1 General

Numerous risk assessment and mitigation studies have demonstrated the importance of system interdependency and as such this issue should also be examined in the context of resilience. Interdependencies refer to the impact that a system may have on one or more other systems, either because their components are located at a small distance, e.g. debris from damaged buildings may block roads, or because one needs input from the other to perform its function, e.g. pumps in water distribution networks run on electric power. In the second case, it is possible that damage to a system will produce cascade effects and lead to disproportionate consequences. Assume for example that after an earthquake, some distribution lines for electric power are damaged and a number of buildings are on fire. Because of loss of power, the water distribution system will be malfunctioning and water will not be available to fire fighters in all areas where it is needed. In the next paragraphs, examples of interdependent systems are discussed for the event of a seismic hazard. Where methods for quantitative assessment are developed, they measure functionality immediately after the earthquake and may need to be updated during the recovery phase.

3.4.2 Buildings and roads/lifelines

The interdependency between buildings and roads following a seismic event was studied by Arcidiacono et al (2012) in a probabilistic framework and considering the reduction of the number of lanes available for traffic due to the presence of debris on the roads. For a single road segment *i*, the probability of exceeding damage state *k* is taken as the maximum among those for the buildings facing this road:

$$PDS_{i,k}^{T} = \max(PDS_{j,k}^{B}) \tag{31}$$

For the case of a district, the probability of damage of each building is weighted by its perimeter p_j^B and their sum is normalised by the total length of roads in the district:

$$PDS_{i,k}^{T} = \frac{\sum p_j^B PDS_{j,k}^{B}}{\sum l_j} \leq 1 \tag{32}$$

In the previous two equations, the superscripts ^{T} and ^{B} are respectively for roads and buildings. The number of available lanes in the *i*-th road segment, nl_i, is then:

$$nl_i = nl_i(t_0)\left(1 - \frac{\sum w_k DPDS_{i,k}^{T}}{\sum w_k}\right) \tag{33}$$

where $nl_i(t_0)$ is the number of available lanes in segment *i* before the event, $w_k = 0.1k$ are weight coefficients and, considering five damage states for buildings, $DPDS_{i,0}^{T} = 1 - PDS_{i,1}^{T}$, $DPDS_{i,k}^{T} = PDS_{i,k}^{T} - PDS_{i,k+1}^{T}$ for k = 1,2,3 and $DPDS_{i,4}^{T} = PDS_{i,4}^{T}$.

The inverse interdependency is that a building that is not accessible through the road network will be impossible to repair and the beginning of the recovery period will be the end of the recovery of the access road(s). Similarly, a building that is not supplied with essential services, such as energy and water, will not be functional, even if it has suffered no structural and non-structural damage after an event.

3.4.3 Economic activities and lifelines

Business recovery is heavily dependent on restoration of lifelines. A survey of businesses following the 1994 Northridge earthquake, found that 58 % of business closures were in part due to lack of electricity, 56 % due to the inability of employees to get to work, and 50 % due to lack of telephone service (Tierney 1997). Similar data was collected by Gordon et al (1998). The most important reason for business interruption reported by company officials was the time spent by employees to see to personal matters following the earthquake. Structural damage and interruption of utility services were respectively the second and third most common causes, followed by inhibited access of employees and customers. Overall, 27 % of the business interruption cost, corresponding to a job loss of more than 15700 person-years, was attributed to damage of the transportation network.

3.4.4 Structural damage and organisational aspects in hospitals

Cimellaro et al (2011a) studied the influence of physical damage on the organisational capacity of a hospital. A ‘penalty factor’, PF_i, was proposed to reflect the effect that damage of structural and non-structural components has on the organisational components of the hospital system. It takes the form:

$$PF_i = a(P_1 - P_2) + b(P_2 - P_3) + c(P_3 - P_4) + dP_4 \leq 1 \tag{34}$$

where P_i is the probability that a component will be in the i-th damage state and a, b, c and d are parameters that depend on the thresholds between the four damage states.

A global penalty factor, PF_{tot}, is then computed as:

$$PF_{tot} = w_1 PF_{str} + \frac{1 - w_1}{n} \sum PF_i \leq 1 \tag{35}$$

where w_1 is a weighting factor for the structural components taken as the ratio of the cost of the structural components to the overall cost of the building, PF_{str} is the penalty factor for the structural components, PF_i is the penalty factor for the i-th non-structural component and n is the number of non-structural components. For the estimation of the functionality of the hospital, the number of available emergency rooms, operating rooms and beds is multiplied by the global penalty factor.

3.4.5 Water and electric power distribution networks

Dueñas-Osorio et al (2007) developed a probabilistic framework for the study of interdependent infrastructures. It is based on geographical immediacy of the components belonging to the different networks and accounts for the strength of coupling. The framework produces system fragility curves by performing Monte Carlo simulations, where the interdependency is expressed by the probability of failure of the j-th element of the water network, $P(W_j)$, conditional on the failure of the i-th element of the power network located in its proximity, $P(P_j)$. The probabilities of exceeding 20, 50 and 80 % connectivity loss in the water distribution network are plotted versus the peak ground acceleration in Fig. 3.5 for different levels of coupling with the electric power network. An increase in fragility is observed as the coupling becomes stronger, from $P(W_j|P_i) = P(W_j)$ for totally independent networks to $P(W_j|P_i) = 1.0$ for totally dependent networks. The effect of interdependency is more obvious for higher values of connectivity loss.

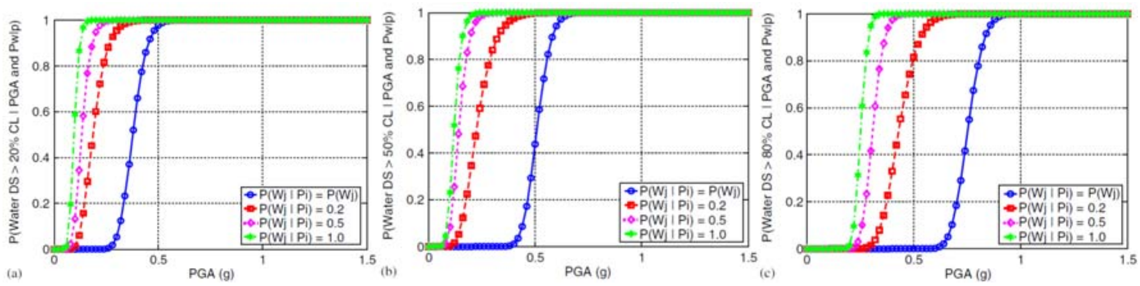

Fig. 3.5 Interdependent fragility curves for water network by Dueñas-Osorio et al (2007): 20 (a), 50 (b) and 80 % connectivity loss (c)

3.5 OPERATIVE CASE STUDIES

Three case studies from literature are briefly presented in this section, with the aim to illustrate how the concept of resilience may be useful in practical applications. The first two exemplify the use of resilience, together with cost, for the comparative evaluation of rehabilitation strategies. The third example serves the same scope and in addition investigates the effect of functionality metrics on the estimated value of resilience.

Cimellaro et al (2010) performed resilience assessment of a network of hospitals in the Memphis area. Five of the hospitals are concrete shear wall systems and one is made of unreinforced masonry. Resilience of the system was assessed for four retrofit strategies: no action, retrofit to meet the requirements for the life-safety or the immediate occupancy performance levels (design to a ‘medium-level’ or ‘high-level’ seismic code, respectively) and rebuild the hospitals to satisfy special requirements for essential facilities. The results are compared in Fig. 3.6, where it is shown that for retrofit to achieve higher levels of performance, resilience is higher and time to full recovery is lower, at the expense of higher initial cost. This exercise is useful for decision-makers to select the intervention that fulfils the desired resilience and budget limitations.

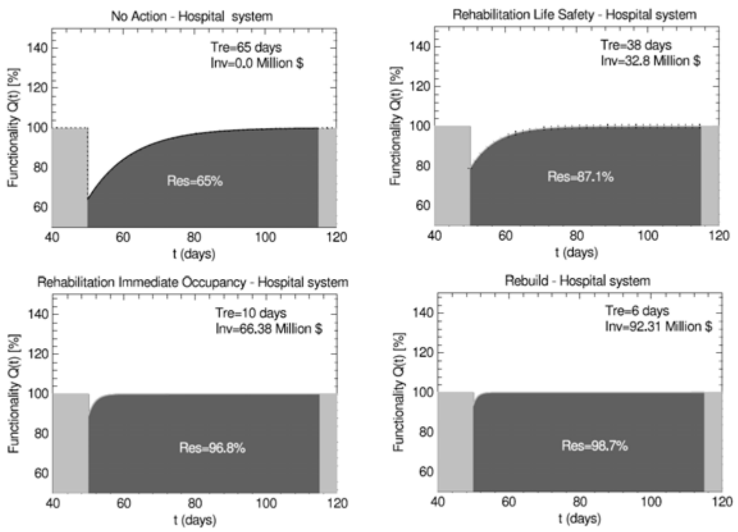

Fig. 3.6 Resilience of hospital system for different retrofit strategies (Cimellaro et al 2010)

Bocchini and Frangopol (2011) present a theoretical example of rehabilitation of a highway network following an earthquake. The objectives are to maximise resilience and minimise cost, under time, budget and operational constraints. They examine three alternative recovery paths and compare them in terms of resilience, cost and time until full recovery, as shown in Fig. 3.7. Strategies A and B lead to full recovery at the same time and have similar values of resilience, but the cost of A is much lower. Considering all criteria, strategy C may be considered the optimal solution, as it is the most economic and has the highest resilience, although it leads to full recovery later than desired.

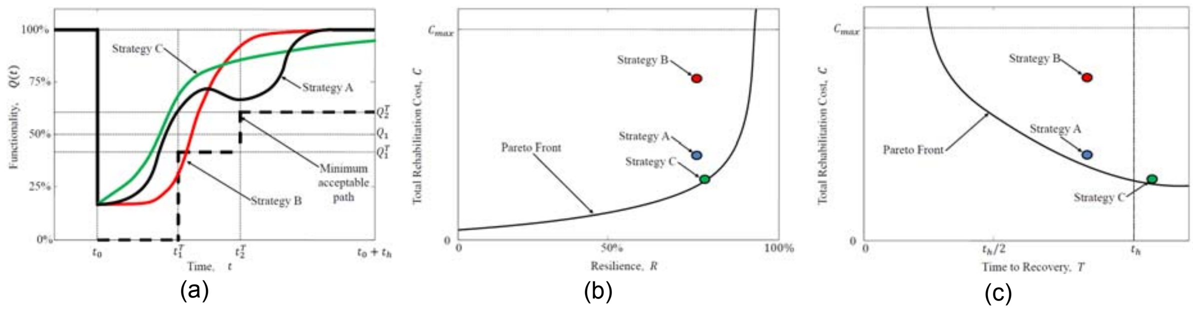

Fig. 3.7 Comparison of alternative recovery strategies for a highway network (Bocchini and Frangopol 2011): functionality vs time (a), cost vs resilience (b) and cost vs recovery time (c)

A theoretical case study is reported in the following to illustrate how the selection of metrics may influence the calculated values of resilience and consequently the convenience of recovery strategies. Henry and Ramirez-Marquez (2012) studied the simplified road network shown in Fig. 3.8(a) for two possible disruptive events – the one discussed in the following causes failure of edges OA, OB, OC, AB and BC – and two recovery strategies, each one following a different sequence of restoration of segments. Three functionality metrics were employed: the shortest path from node O to node T, the maximum flow between nodes O and T and the length of usable edges normalised to the total road length in the network before the event. The plots in Fig. 3.8(b, c) show the values of resilience versus time for the two strategies and the three metrics. Note that resilience is measured as the ratio of time-dependent recovery to the maximum loss immediately after the disruptive event. If the first functionality measure is used, the first strategy is superior – the system recovers almost fully at 20 days, whereas for the second strategy it is fully restored approximately 60 days after the event. Also using the second measure, functionality is restored earlier for strategy 1 than for strategy 2. Nonetheless, the ranking of recovery strategies is inverted, if the third measure is considered.

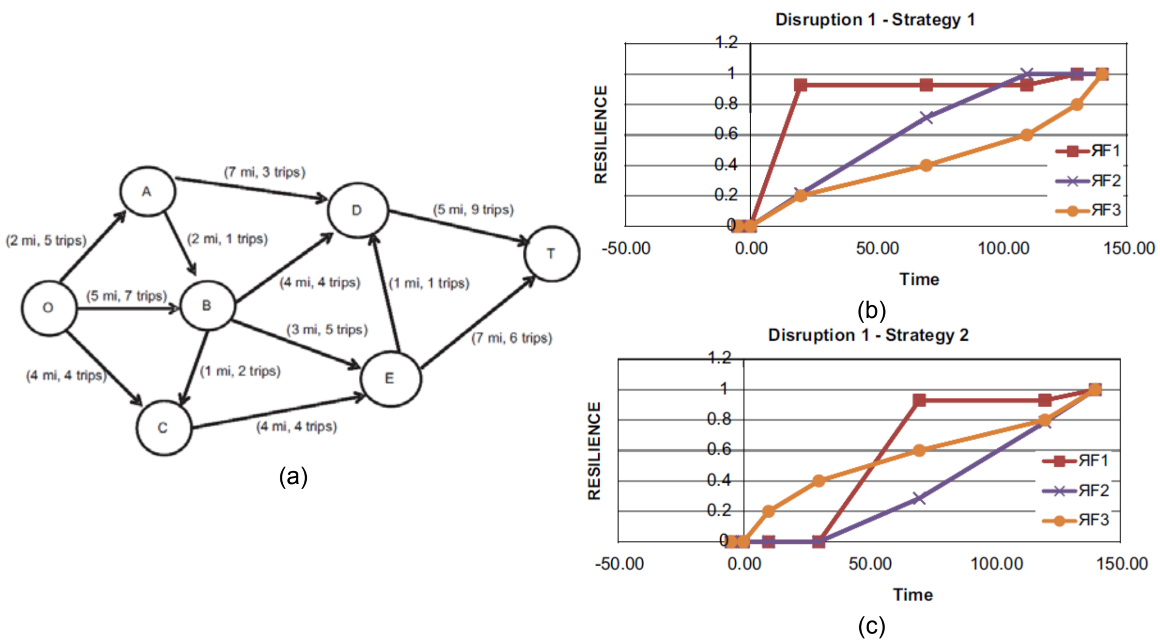

Fig. 3.8 Road network (a) and resilience vs time for strategies 1 (b) and 2 (c), from Henry and Ramirez-Marquez (2012)

4 Uncertainties in resilience

Generally, uncertainties should be considered for the values of functionality and time corresponding to all the characteristic points of the functionality curve, as shown schematically in Fig. 4.1. A simple way to account for uncertainty in the initial loss of functionality is through the use of fragility functions that provide the probability that a component will reach a specific damage state, conditional on the intensity of the hazard. Bruneau and Reinhorn (2007), for example, incorporated seismic fragility curves in a procedure developed with the aim to achieve a desired value of seismic resilience for a hospital. According to this procedure, iterations are performed in case structural interventions are needed and the corresponding fragility curves are adjusted to reflect the response of damaged or retrofitted components.

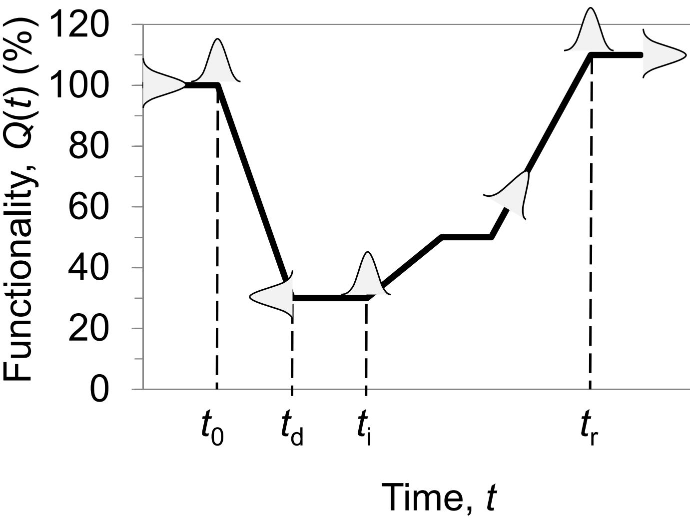

Fig. 4.1 Uncertainties in resilience assessment, adapted from Decò et al (2013)

Five random variables may be considered to come into play in the calculation of resilience: intensity measure *I*, response or demand parameters *D*, performance measures *PM*, losses *L* and recovery time T_{RE} (Cimellaro et al 2009). The joint probability density function may be written as function of the conditional probability density functions:

$$f_{I,D,PM,L,T_{RE}} = f(T_{\mathrm{RE}}|I,PM,D,L)\ f(L|PM,D,I)\ f(PM|D,I)\ f(D|I)\ \mathrm{f}(I_{\mathrm{TLC}} \geq i^*) \tag{36}$$

The first term stands for the uncertainty in the recovery time, which depends on all remaining variables. The second term reflects the uncertainty of the loss estimation model, while the third one describes the uncertainties related to the structural model and analysis. The last term is related to the probability of exceeding a seismic intensity value *i** in a given time period T_{LC}. Then, the mean value of resilience may be written as:

$$m_R = \int_I \int_D \int_{PM} \int_L \int_{T_{RE}} R f_{I,D,PM,L,T_{RE}}\, \partial T_{RE}\, \partial L\, \partial PM\, \partial D\, \partial I \tag{37}$$

Decò et al (2013) developed a probabilistic framework for seismic resilience assessment of bridges. The aim is the pre-event comparison of recovery strategies in terms of resilience, rapidity and cost. The procedure makes use of a decision tree that contains the post-event damage states of the bridge as the first branches. For each damage state, four alternative branches are considered: they represent fast, average and slow recovery patterns as well as no action. A portfolio of recovery strategies is then defined by a number of combinations of the outcomes of the decision tree; a strategy comprises a single recovery pattern for each damage state. Assuming a seismic scenario, the probability of reaching each damage state is estimated by means of fragility curves. The following step is a Monte Carlo analysis considering the idle time, recovery time and immediate post-event functionality as random variables assuming appropriate distributions. For each strategy, the Monte Carlo simulation will yield the mean value and standard deviation of resilience, rapidity and total cost. Total costs include the retrofit/reconstruction of the bridge, the removal of debris and the indirect costs due to traffic disruption.

The mean values of resilience, cost and recovery time for the examined set of strategies are indicatively shown in Fig. 4.2 for an application to a real bridge. Note that strategies that exceed the available budget are shown as 'unavailable'; an x sign is used for strategies that include the no-action option for a damage state and therefore full recovery is not possible. Overall, resilience and rapidity are affected by large uncertainty, but strategies with higher resilience and rapidity have relatively small standard deviations. As expected, the most expensive strategy provides the highest resilience and shortest time to full recovery. However, it can be noticed that resilience does not increase considerably when a much greater investment is provided, whereas the reduction of indirect costs is more significant. Other results, not illustrated here, indicate that when the earthquake magnitude increases, the decrease of resilience is relatively low and the cost rises exponentially. It is also shown that the idle time has an almost linear effect on resilience and indirect costs.

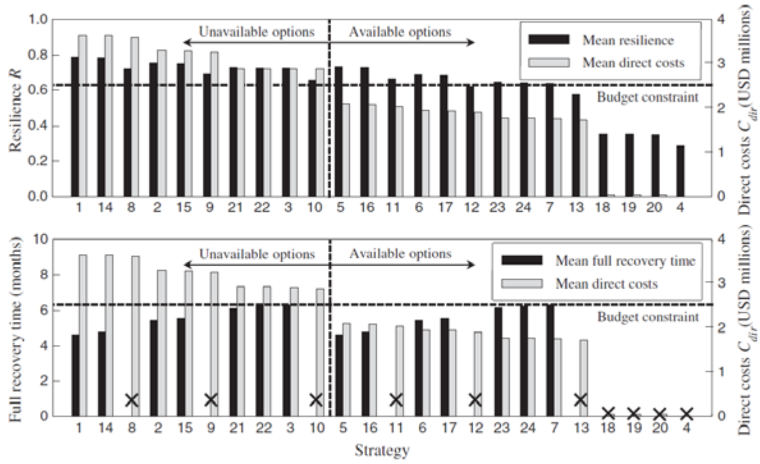

Fig. 4.2 Histograms of expected resilience (top) and expected full recovery time (bottom) versus expected direct costs (Decò et al 2013)

Finally, entropy was proposed by Tamvakis and Xenidis (2013) as a probabilistic metric of resilience. Depending on the measure, entropy expresses the probability that a system or its components will be in one among all possible states. Operating on the hazard side, Francis and Bekera (2014) suggested the use of an entropy-weighted measure of resilience for events that are characterised by high uncertainty regarding their recurrence and intensity. The functionality metric is multiplied by this entropy-based weight, which expresses the subjective views of experts and stakeholders on the probability of occurrence of an event and on the value of its intensity measure. The resulting metric gives more weight to highly improbable events over more likely ones.

5 Resilience for multiple hazards and events

5.1 MULTIPLE HAZARDS

As resilience covers all aspects of the quality of life of a community and its response to disruptive events, it also has to contemplate all possible hazards that may threaten the community. While the focus of this report remains on seismic resilience, some issues relevant for resilience against multiple hazards are discussed in the following. Besides, it is argued that principles and measures to reduce losses and in general to improve resilience against earthquakes can be applied to other hazards during the life-cycle of the asset, or vice versa (Dyke et al 2010, NRC 2011).

Qualitative and quantitative approaches exist for multi-hazard assessment (Kappes et al 2012). The former employ classification schemes to compare hazards, while the latter make use of indices based on previous data on the occurrence and the intensity of the hazard, the affected area, the impact on people and the economy, etc. A difficulty arises from the different measures used for each hazard. To overcome this, multiple hazards are more easily assessed at the risk level, when measured in a common unit such as monetary loss or number of victims.

A framework for resilience to multiple hazards has yet to be developed. As for multi-hazard assessment, it is essential to harmonise functionality metrics and to establish a common reference area and period of time for all hazards. Depending on the case, functionality may be measured in terms of the number of casualties or economic loss originating from structural damage (e.g. Marzocchi et al 2009, Li and van de Lindt 2012). The reference time may be the conventional working life of the asset, or some other period defined by stakeholders. On the other hand, Grünthal et al (2006) proposed to calculate the annual probability of exceedance of a level of economic loss and then to compare losses due to different hazards for the same annual probability of exceedance. Having established the loss, or risk, for each hazard, a simple approach is to proceed with the calculation of resilience separately for each of them.

A procedure for the quantification of the cumulative effect of random hazards by a single measure was proposed by Ouyang et al (2012). The expected annual resilience for multiple hazards is defined as the mean ratio of the area below the functionality curve to the area below the functionality curve of the intact asset (target performance curve) during a year. Neglecting the co-occurrence of hazards and assuming that in the absence of disruptive events the asset will maintain the initial functionality, the expected annual resilience is calculated as:

$$AR = 1 - \frac{1}{T}\sum_{h=1}^{H} v_h \int_{q_h} E[AIA_h(q_h)]\varphi_h(q_h)\partial q_h \tag{38}$$

where T is the reference period of one year, v_h is the occurrence rate of hazard h per year, $E[\bullet]$ is the expected value, AIA_h is the area between the target performance curve and the actual performance curve following the event, q_h is the hazard intensity and φ_h is the probability density function. The expected annual resilience is calculated through Monte-Carlo analysis considering hazard intensities as random variables and employing fragility curves to estimate the probability of damage of components. Assuming also a restoration curve for each component and damage state, a value of resilience is calculated for each sample of multi-hazard intensities. A sufficiently large number of random samples is selected and the expected annual resilience is calculated from Eq. (38).

5.2 MULTIPLE EVENTS

Considering all possible events and their intensities during the life-cycle of a system, Cimellaro et al (2006b) proposed the following probabilistic expression of resilience:

$$R = \frac{1}{N_I}\sum_{I=1}^{N_I}\left\{\frac{1}{N_E}\sum_{E=1}^{N_E}\frac{P_E(0,T_{LC})}{t_r - t_0}\int_{t_0}^{t_r}\left\{1 - L(I,t_r)\left[H(t-t_0) - H(t-t_r)\right]\alpha_R f_{\mathrm{Rec}}(t,t_0,t_r)\right\}\partial t\right\}P(I) \tag{39}$$

N_I is the number of intensities expected during the life-cycle of the system, T_{LC}, N_E is the number of expected events, $P_E(0,T_{LC})$ is the probability that an event happens E times during the life-cycle, $L(I,t_r)$ is the loss function, $H(t)$ is the Heaviside step function, α_R is a recovery factor, $f_{REC}(t,t_0,t_r)$ is the recovery function and $P(I)$ is the probability that an event of intensity I occurs during the life-cycle.

Zobel and Khansa (2014) developed a concept for an ‘equivalent’ resilience against multiple events, using the definition in Eq. (16). Consider an event at time t_0 that causes X_1 loss of functionality and at $t_0 + T_1$ has recovered X_1’. A second event occurs at $t_0 + T_1$, causing X_2 functionality loss with respect to the initial conditions at t_0. Full recovery after both events is achieved at $t_0 + T_1 + T_2$. Generalising this example, the total resilience for consecutive events is:

$$R = 1 - \sum_i \frac{(X_i + X_i')T_i}{2T^*} \tag{40}$$

where T_i is the time needed to recover from X_i to X_i’. If $T = \Sigma T_i$ is the total time to recovery, the average loss of functionality, $X/2$, may be defined as:

$$R = 1 - (X/2)T/T^* \Rightarrow (X/2) = (1-R)T^*/T \tag{41}$$

The total resilience according to Eq. (40) may correspond to a multitude of consecutive events. It is then on interest to define a ‘partial’ resilience that is associated to the i-th event:

$$R_i = 1 - \frac{(X_i + X_i')T_i}{2T^*} \tag{42}$$

Partial and global resilience are related according to the following expression:

$$R = 1 - \sum_i (1 - R_i) \tag{43}$$

The methodologies described above assume that hazards (section 5.1) and events (section 5.2) are independent. Equations (38) and (39) consider also the probabilities of occurrence. Eventually, expected losses are summed and values of resilience are averaged. An extension to the case of interacting hazards or cascade effects requires more complex calculations that make use of event trees or Bayesian networks, e.g. as described by Nadim and Liu (2013) for multi-hazard risk assessment.

6 Resilience and sustainability

Sustainable development is often defined as the one that '*meets the needs of the present without compromising the ability of future generations to meet their own needs*' (UN 1987). Following the ever-increasing social demand, sustainability assessment has been applied to a variety of subjects, including construction works and infrastructures, and a number of national assessment schemes has been produced. International consensus has also been achieved with the development of standards.

The social and environmental aspects of sustainability are related to seismic resilience through the effects of earthquakes on human health and the environment on one hand, and through the environmental impact of materials and processes, both for the construction phase and for retrofit after an event, on the other. As indicated by a case study discussed in the following, seismic resilience might be in conflict with environmental sustainability. Therefore, life-cycle assessment is necessary to estimate the economic cost of alternative solutions and assist in decision-making.

Recently, Bocchini et al (2014) identified a number of similarities and differences among resilience and sustainability. In detail, their quantification employs calculation methods, including structural analysis, to estimate social and economic impacts and their associated costs over the whole life cycle. On the other hand, sustainability refers to regular conditions of very low uncertainty, while resilience deals with single events with lower probability of occurrence (and possibly high consequences). An additional difference is that sustainability is assessed for a single structure, whereas resilience is calculated for a system or a region.

Interaction between resilience and sustainability takes the form of impacts of natural hazards on human health and the environment, further to the damage to buildings and infrastructures. Examples include the creation of lakes due to blocked streams, the soil erosion due to denudation and the change of land use as a result of earthquake-induced landslides (Lin et al 2008); the pollution of air due to burning of chemicals, demolition of damaged buildings and traffic congestion following a major earthquake (Gotoh et al 2002); and the contamination of drinking and floodwater as well as the increase of solid/demolition waste following hurricane Katrina (Reible 2007). Environmental aspects are important also during the reconstruction phase. As reported by Khazai et al (2006), the increased demand for construction materials in a very short time may lead to shortage of natural building materials and subsequently to environmental impacts like coastal erosion, saline intrusion and illegal mining. Interaction may occur also in the opposite direction: a stressed environment, possibly due to human actions, is more susceptible to damage in the event of natural hazards such as floods, storms and hurricanes (Cutter et al 2008).

Whitehead and Rose (2009) estimated the socio-environmental benefits of natural hazards mitigation projects in terms of water quality, recreation, hazardous waste, aesthetics and preservation of cultural heritage. Only a small portion of the examined earthquake mitigation projects had potential environmental benefits, which accounted for less than 1 % of the total benefits. However, this result should be seen as a preliminary indication, as it covers few projects and environmental impacts.

A unified approach for the simultaneous sustainability and seismic resilience assessment of infrastructures was developed by Bocchini et al (2014) and applied for the comparison of two alternative structural configurations for a regular highway overpass. For the sustainability analysis, life-cycle assessment takes into account i) the material and labour cost during the construction and ordinary maintenance phases, ii) the external (social and environmental) costs because to traffic delays during the whole life cycle and iii) the environmental impact of construction products in terms of global warming potential, primary energy use, etc. Seismic resilience assessment is also performed for the life-cycle and considers several seismic scenarios with their associated probabilities of occurrence. The direct costs are those associated to the expected structural damage for each earthquake and are calculated using fragility curves. They are added to the indirect costs arising from the detour of traffic during the recovery of the bridge. Both resilience and sustainability costs are expressed in monetary units. Although this example is theoretical and the findings should not be generalised, it gives rise to interesting observations. First, the indirect costs are an order of magnitude higher than the direct ones, which points to the significant potential for savings if structures are designed for fast recovery and higher resilience. Besides, the need to consider both aspects – and the balance between them – is highlighted by the fact that the sustainability impact, currently not included in the design criteria, is around three times higher than the resilience impact, which depends mostly on structural damage, and that the most resilient system performs worse in terms of sustainability.

7 Closing remarks

The concept of resilience has been introduced in earthquake engineering in order to address the consequences of seismic events on the society at large, the economy and the environment, further to the risk of physical damage and casualties. It becomes obvious that it covers a broad range of aspects and hence the multitude of definitions and methodologies proposed in previous works. It may be argued that the initial confusion at the conceptual level has been mostly clarified and that significant efforts have been dedicated by the earthquake engineering research community on the practical application of resilience assessment, including metrics, calculation methods and treatment of uncertainties.

Several studies have demonstrated how resilience may be used by decision makers to evaluate the effectiveness of mitigation measures, based not only on the initial damage, but also on the recovery time and associated costs (i.e. the investment needed to achieve higher resilience before the occurrence of an event, against the sum of expected direct and indirect losses and the cost of recovery actions). Resilience assessment procedures have been extended to consider the multitude of events and hazards that may affect the structure or system during its lifetime. Ultimately, it is up to society to decide on the cost and disturbance, in terms of functionality loss and recovery time, it is willing to sustain.

However, the literature review presented in the previous sections of this report reveals a number of recurrent topics where further research is needed. The overall objective is to achieve consistency in definitions, metrics and methods with a view to developing, at a later stage, standards for resilience assessment. Specific topics that need to be further investigated are listed in the following:

- identification of the most appropriate performance measures for each asset and system;
- development of a relationship between structural and non-structural damage on one side and functionality and recovery on the other (Mieler and Uma 2014);
- definition of boundaries in relation to space (single structure, local system, regional scale, etc.), time and the aspects (technical, social, economic, etc.), to consider in resilience assessment;
- collection and dissemination of relevant data according to a common format;
- calibration of recovery functions using existing data on the post-earthquake performance of infrastructures, such as the work of Chang and Nojima (2001) on the restoration of the highway and railway networks after the 1995 Hyogoken-Nanbu earthquake, Reed et al (2009) on the recovery of the electric power network in Louisiana and Mississippi after the Katrina hurricane and Cimellaro et al (2011a) on the functionality of a hospital in Buffalo based on collected data during the Northridge earthquake;
- refinement of probabilistic assessment methods, considering the most suitable distributions for the random parameters and aiming at the reduction of uncertainties;
- validation of methods, including the treatment of interdependencies, through application to real-life complex systems (Henry and Ramirez-Marquez 2012);

- critical analysis of key structure types and their interaction with other physical infrastructures and components, including the cost of implementing measures to enhance resilience and the expected loss reduction (Gilbert 2010);
- development of a holistic design methodology for resilience against multiple hazards and sustainability;
- integration of engineering with organizational response and societal impacts (Chang and Shinozuka 2004).

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